Providing Real-Time Message Delivery on Opportunistic Networks

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***Abstract*—IoT systems monitoring or controlling the behaviour of smart environments frequently require to count on real-time message delivery, in order to support decision making and eventually coordinate the individual behavior of their system components. Several initiatives propose the use of opportunistic networks to address this requirement, but none of them support message delivery considering time constraints. Therefore, the support that they provide is partially suitable for conducting real-time monitoring and control of smart environments. In order to address that challenge, this paper proposes a message propagation model for opportunistic networks that considers the participation of heterogeneous devices, and guarantees the real-time behavior of the network by bounding the maximum delay for messages transmission. The message propagation is modeled using an analytical approach that reduces the effort of prototyping and analyzing the properties of these networks. Two running examples, based on disaster relief efforts, are used to illustrate the feasibility of implementing the proposed message dissemination model on opportunistic networks, and thus to allow real-time communication in the field. These results showed that is feasible not only the implementation of these networks, but also their representation using an analytical approach. The networks for both example scenarios were then simulated to confirm the results obtained using the analytical approach. Given the positive results, the proposed model and its representation open several opportunities to model smart environments and design IoT systems that require real-time communication in opportunistic networks.**

***Index Terms*—Real-Time Message Delivery, Opportunistic Networks, Analytic Approach, IoT Ecosystem, Disaster Relief Scenarios.**

I. Introduction

Several IoT-based systems are used to monitor critical components (from patients with chronic diseases to physical or natural infrastructure) and also control the behavior of smart environments in order to make these solutions not only smarter, but also more flexible and context-aware. In particular application domains, like in smart homes or smart responses to natural disasters, these systems need to count on real-time communication among their components and participants, since the effectiveness of these solutions is usually a mandatory requirement for the supporting systems.

Given the diversity of autonomous devices and actors available in these environments, the use of Opportunistic Networks (OppNets) rises as one of the most widely accepted alternative to provide communication support, given their flexibility and low effort of deployment. However, the current proposals for implementing OppNets are limited when they intend to consider a wide variety of devices, time-constraints for message delivery, or both of them [1]. Special protocols for machine-to-machine communications, such as MQTT (Message Queue Telemetry Transport) or CoAP (Constrained Application Protocol) are being proposed in IoT; but they require whole implementation of the IP stack.

In order to help address that limitation, this paper proposes a bounded message propagation model for OppNets that involves IoT-enabled devices as nodes. An analytical approach is used to represent both, the propagation model and the IoT-based communication infrastructure. This type of approach eases the modeling of OppNets for particular application domains, and reduces the effort of prototyping and evolving the networks designs, compared to using simulations. Therefore, the analytical representation of the propagation model also represents a contribution of this paper.

The proposed model introduces two message scheduling policies for these networks and computes the maximum delay for the message delivery. Using this information, we demonstrate the feasibility of implementing a real-time OppNet. The potential impact of the propagation model is analyzed using two running examples related to disaster relief efforts. The first example represents a synthetic case, and the second one is based on a real-world incident. In both cases, the article shows how the introduction of the proposed message dissemination model, as a complement of the UHF/VHF radio systems, allows improving the communication support among first responders during disaster relief efforts. The results obtained using the anlytical approach were highly positive and they were confirmed through simulations. Therefore, the message dissemination model and also its analytical specification represent the main contributions of this paper. The model can be used to support OppNet-based real-time communication in several application domains (e.g., in remote monitoring), and the analytical specification of the model allows to represent, analyze and evolve these networks spending an effort significantly lower than using simulations. Therefore, this proposal opens several opportunities to design, implement and evaluate IoT-based solutions that require real-time support on OppNets.

This paper extends the authors' previous work reported in [2], by incorporating proofs to lemmas and a evaluation section with both real and synthetic cases to validate to the proposal. Particularly, a synthetic case and a case study based on a real incident were used to evaluate the proposed model. This evaluation used both, an analytical approach and simulations to show the consistency of the results and its applicability in real scenarios.

Next section briefly introduces background information on first response activities and discusses the related work on message delivery over OppNets considering time restrictions. Section III describes the proposed model emphasizing its role as facilitator of the message propagation process. Section IV shows the schedulability analysis of the proposed model considering two message scheduling policies. Section V presents the performance evaluation of the model using a synthetic case and Section VI evaluates it using a real-world incident as study scenario. These evaluations show the properties of the proposed model using an analytical approach. These results were then confirmed using simulations, which are shown and discussed in Section VII. Finally, Section VIII presents the conclusions and future work.

II. Background

In order to illustrate the challenges involved in providing real-time communication support on OppNets, we will use the disaster relief efforts as study scenario. Counting on communication support in this scenario is mandatory to allow coordination and collaboration among the involved people [3], [4], and thus reduce the impact of extreme events on the civil population. Next we briefly characterize this application domain, and then discuss the main proposals that could be used to provide communication support to first responders working in the field.

A. Characterization of the Disaster Relief Scenarios

In first response processes there is usually an incident commander (IC), who is in charge of coordinating all activities in the field, and also asking for external support; e.g., specialized equipment and human resources. This commander is located in a command post at the border of the working area. Several other teams participate in these efforts, which are usually in charge of conducting particular activities according to the organization they belong to; for instance, to secure the affected area (police service), conduct search-and-rescue operations (firefighting companies) and provide first-aids to injured people (emergency medical service). Every team of each organization has a leader that should make local decisions (for his team) and coordinate the activities with other team leaders and the IC.

Typically, VHF/UHF radio systems are used to conduct communication and coordination among the team leaders and the IC, since these systems are quick to deploy, provide quite reliable channels to exchange voice messages, allows people mobility and are temporarily autonomous of power supply [3]. Although useful, radio systems have several shortcomings, such as limited number of available channels, incapability to transmit digital information, inability to manage message interference (e.g., the exchanged messages are frequently overwritten by more powerful devices or mixed by the antennas) [5], [6]. These analog systems are limited to support resilient network protocols and topologies, keep a multi-organizational coordination, and maintain information consistency [3].

Without an appropriate communication support, the decisions made by the incident commander and team leaders are based mainly on their own experience, since little or no information is available to support such an activity. Thus, the coordination among teams becomes a challenge almost impossible to overcome. Given this situation, it is not surprising to see improvisation in the field [7], which usually impact negatively on the emergency response process, as observed in the Yarnell Hill Fire (2013) [8] and also in World Trade Center (2001) [9].

Given these limitations, several researchers and first response organizations have shown the need of counting on digital communication in the field, as a complement of UHF/VHF radio systems. The solution should support message exchange among first responders that use several types of devices in a scenario with uncertain communication stability and bandwidth.

Although the cellular network represents a potential alternative to play such role, the typical collapses of the telephone lines and power networks make this option no feasible. In this sense, most organizations participating in first responses are exploring the use of other digital communication alternatives to complement their radio systems. Next section presents and discusses some of the most prominent alternatives.

B. Communication Support in Disaster Relief Efforts

Many communication infrastructures have also been proposed to try deal with the need of providing suitable digital communication in unstable scenarios, like in disaster relief efforts. Most proposals involve mobile computing devices and are based on mobile ad hoc networks or opportunistic networks [10], [11], [12], [13]. Recently, these infrastructures have evolved toward Internet of Thing (IoT) scenarios, where many heterogeneous devices interconnected via OppNets, interact among them to provide information support and also additional communication and coordination capability to first responders [14], [15]. The current availability of IoT-enabled devices can help increase the resilience of the communication in the field, by leveraging their spontaneous wireless networking capabilities while the conventional communication infrastructure is out of service [16].

In [7] the use of an opportunistic network to support collaborative applications (like the one needed in first responses) is analyzed, and the first concepts of time constraints are introduced. In [17] the authors present an analysis of real-time traffic for the case of FIFO scheduling at the level of communication gateway, but without considering priorities in the message delivery. This aspect is critical in scenarios like disaster reliefs, since the delivery of priority messages (e.g., evacuation alarms or orders from the IC) should be ensured regardless the presence of other messages in the network.

In [18] the authors analyze the stochastic performance of different message routing strategies under several inter-meeting times distributions. Such a proposal does not contemplate a real-time behavior, as no deterministic guarantee is provided for the message delivery. Additionally, in [19], the authors compute a probabilistic guarantee for the message transmission delay in an OppNet with exponential inter-meeting times. Although this kind of bound can be used to model expected behavior of a network, it is not useful to represent real-time messages delivery when a deterministic guarantee is required.

The use of mules has been also proposed in previous works, as a way to keep the network resilience in case of nodes failures, or to transport data in distributed meshes that cover wide areas without communications infrastructure (or with limited connections among nodes). In [20] different techniques are proposed to determine the mules paths considering the geographic conditions and the available infrastructure. In [21] a trade-off analysis is presented to try minimize the number of mules in the system, while guaranteeing both throughput requirements and the use of the optimum path to cover a physical area. The model presented in [2] considers the use of mules to support real-time communications between search-and-rescue teams; however, such a work does not include a theoretical validation or experimental results that show the model performance.

Regardless the usefulness of the previous works, they do not consider accomplishing with real-time restrictions for the message delivery in uncertain communication scenarios, like in disaster affected areas. Overcome this limitation would allow to reduce the impact of these events, given the time constraints existing to conduct the first response activities during the golden relief time (i.e., during the first 72 hours) [6]. In this sense, the message dissemination model that is presented in the next section takes a step forward, trying to deal with a communication challenge that still remains open. The proposal also opens the door to the participation of the IoT world in these solutions, since a wide variety of computing and sensing devices can become part of this ecosystem.

III. System Model

Considering the communication restrictions indicated in the previous section, this proposal is based on an OppNet built upon a multi-hop chain that transfers information from the incident commander to the teams in the field and back. As there are time restrictions for the message delivery, the transmissions have real-time characteristics; therefore, the message end-to-end delay should be predictable. Moreover, this solution must allow the participation of a wide variety of computing devices, ranging from autonomous vehicles to smart-watches or similar.

Fig. 1 shows a deployment of first response teams in the field, and the typical actors involved in a disaster relief ecosystem. As mentioned before, the activities of first response teams are coordinated by the incident commander (IC) located at the command post (CP). Each team has a gateway, i.e., a person/device who is in charge of coordinating activities with other teams. This node receives information from its team members and transfers it to the IC using an OppNet. At the same time, the gateway receives the orders and recommendations from the IC, and transmits them to the team members. Here we can see a hierarchical communication structure that starts either at the head of the system or at the leaves depending on every case.

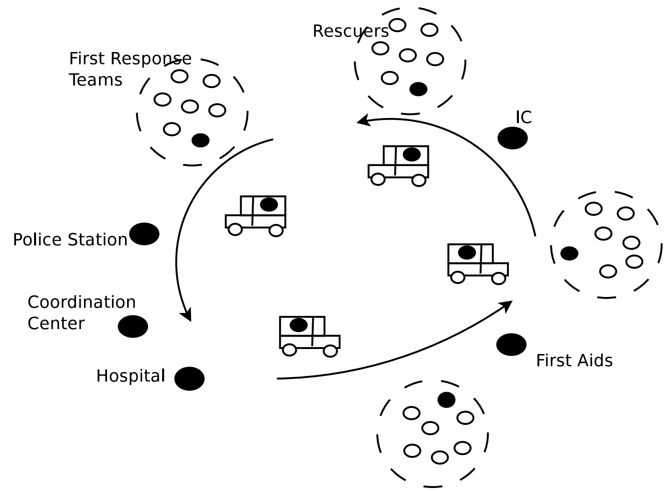

Fig. 1. Mules routing for emergency handling. Gateways are marked in black; small black circles are the gateways of the first response teams

Typically, the area in which teams are deployed is large, and the distance among teams (and also between them and the command post) is too long to allow for a direct communication between them. Therefore, this model proposes the use of mules for transporting messages in both directions, and thus supporting the communication inter-teams. In order to play such a role the mule implements a message queue that can be managed following several scheduling alternatives, like FIFO (First Input, First Output), Round Robin (RR) or Rate Monotonic (RM). The mules follow a predefined path that can be circular, linear or a mix of them. If we assume that they move at constant speed and the gateways representing the teams need to exchange a similar number of messages with other teams (or with the IC), then every gateway will have the same probability to upload messages to the mule when the path is circular. In other case, the probability to upload messages to the mule will depend on combinations of these variables. The fairness of the system can be ensured by defining a message queue for the mule that is large enough as to store all messages pending of being delivered.

These mules can be implemented in different ways, for instance using drones, motorcycles, cars and also bicycles [22]. The information flow in the system has four steps: $N_{i_k} \rightarrow G_i \rightarrow Mule \rightarrow G_j \rightarrow N_{j_l}$ where N denotes a node, and G is the gateway related to that node. We assume no gateway failures given that any node can take over the role of the gateway.

From a communication point of view, each team is indepen-

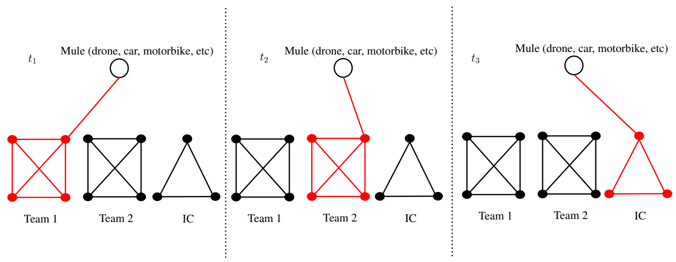

Fig. 2. Space-time graph representing the connectivity model

dent of any other; i.e., the communication being held inside a team has no influence on other teams, either because they are using different channels or because they are so distant that their networks do not interfere with each other. Based on it, we can define the set of gateways: $\mathbf{\Gamma} = \{G_1, G_2, \ldots, G_n\}$. Each of the n gateways is responsible for exchanging messages with the mules and the nodes. That is, mules only communicate with a node through a gateway. For each G_i there is a set of n_i nodes $\mathbf{N}_{G_i} = \{N_{i_1}, N_{i_2}, \ldots, N_{i_n}\}$ that the gateway can interact with. This network can be represented with a space-time graph model [23], where an OppNet is modeled as a sequence of partially connected graphs that change their edges with time based on the nodes mobility.

A. Graph Model

For the case presented here, we can model every first response team as a mesh of nodes where all of them listen the messages of the other team members. Figure 2 shows the sequence of graphs where in each time interval t_i, the mule is in communication range with the gateway of a team. During the last time interval (t_3 in this example), the mule is in contact with the second team, and finally after t_3 it is in contact with the IC.

The union of the three partial graphs produces a connected topology for the whole network. Considering this intermittent behavior and the results reported in [23], we can assume that the network can be represented by a sequence of graphs $\langle V, E^i \rangle$, where V is the set of nodes and E is the set of edges connecting them. However, E is not fixed and they change over time; therefore, for each instance i of the graph, there is a different topology. It is said that the model is connected if there is a finite sequence, such as the graph obtained by composing $\langle V, E^i \cup E^{i+1} \cup \ldots E^{i+n} \rangle$.

In a disaster relief scenario the network is connected as the mules link all the nodes at different instants. However, we can easily see that this model is not sufficient in the study scenario, given the need for timely communication between the nodes and the IC.

In order to compute the end-to-end transmission time between any pair of nodes, it is necessary to compute the different stages, and also consider the time required by the graph to reach the necessary connectivity. Next section presents the real-time model to accomplish this requirement.

B. Real-Time Message Model

In real-time systems, predictability of message delivery is mandatory, as every possible situation should be considered to guarantee the deadlines. Although contention-based protocols work well in average situations, the back-off algorithms introduce uncertainties at the transmission moment, preventing their use in real-time communication scenarios. Time Division Multiple Access (TDMA) protocols are suitable to support real-time operation, as they are able to transmit messages in a predictable (bounded) time, since each node has access to a transmission slot periodically.

In TDMA schemes, time is considered to be slotted and the duration of one slot represents a time unit. The expressions *beginning of slot t* and *instant t* are used interchangeably throughout this paper.

The duration of the slot is determined by the system designer, and it involves parameters like the speed of the mule and the distance (in terms of both, time and space) between two consecutive mules. Clearly, the concept of slot can be used not only for measuring time, but also for calculating distances at constant speed.

Each node $N_i{\in}G_j$ has a set of μ_i messages to transmit, $M(N_i){=}\{m_{ji1}, m_{ji2}, \ldots, m_{ji\mu_i}\}$. Moreover, three types of messages are considered in the system: periodic, sporadic and aperiodic. These messages are described by a tuple $m_{jih}\langle P_{jih}, C_{jih}, D_{jih}, pr_{jih}\rangle$, where P_{jih} is the period or minimum intergeneration time of the message, C_{jih} is the worst case time for transmitting a message, D_{jih} is the deadline and pr_{jih} is the message priority. The first subindex (j) refers to the gateway, the second one to the node (i) in the gateway network and the third one (h), the message in the node.

Both periodic and sporadic messages have to be received before their deadlines, while aperiodic messages have no real-time constraint. Therefore, deadlines associated to aperiodic messages are infinite and they have the lowest priority in the system; they are usually transmitted if there is time. Sporadic messages are aimed to handle emergency calls, such as imminent possible explosions or breakdowns. Once a node generates a periodic or sporadic message, it has to wait for the minimum time (specified by the period) to generate a new message of the same kind.

In addition to the periods and deadlines, let us define the times for executing each of the tasks/message delivery. For the particular case of the message length, it is assumed a constant transfer rate between the mule and the gateway. Therefore, given a certain message length in bits and rate, the C_i can be expressed as the number of time units (slots) needed to transmit the message.

This network model considers a digital communication link among the nodes for two main reasons: (1) it allows to conduct unattended and opportunistic message dissemination in an easy and efficient way, and (2) it does not limit the type of messages that can be exchanged between the nodes (e.g., audio, video, text or images). As mentioned before, this proposal can be used to complement the communication support provided by analog systems, like the UHF/VHF radio systems regularly used by firefighters and police officers.

TABLE I
MODEL NOTATION

G_i	gateways
N_{i_k}	nodes of the team of the gateway G_i
m_n	messages
$M(G_j)$	the set of messages of the gateway G_j
P_i	the period or minimum inter-generation time of m_i
C_i	the worst case length of the message m_i
D_i	the deadline of the message m_i
pr_i	the priority of the message m_i
B	blind window length
W	transmission window length
P_{mule}	the period of the mule
U_{G_j}	the bandwidth demand in the gateway G_j
$U_{\to G_j}$	the bandwidth demand in the mule towards gateway G_j
ω_j	number of messages uploaded to the mule by G_j
$\|MQ\|$	the length of the queue length in G_j
T_{rt}	the round trip time of the mule
$\|MQ_{mule}\|$	the queue length of the mule
T_{trip}	mule worst traveling time
$\mathtt{VMG}$	velocity make good

In the rest of the paper time units (shown in brackets) are omitted. For ease of understanding, Table I summarizes the notation used in the description and analysis of the proposed model.

IV. REAL-TIME SCHEDULABILITY ANALYSIS

In this section, the message scheduling is analyzed from a real-time point of view and considering four scheduling stages: nodes-gateways, gateways-mules, mules-gateways and gateways-nodes. In what follows, for illustration, feasible conditions for each level are determined for two scheduling policies: First In First Out (FIFO) and Rate Monotonic (RM) [24], [25].

The end-to-end worst-case transmission time requires the analysis of each stage in the transmission process. Due to the real-time requirements, the scheduling in each stage is analyzed considering the worst-case situation. Equation 1 establishes the end-to-end delay for a message m_i originated at node $i \in G_j$ and destined to node $h \in G_k$.

$$T_{\mathtt{end\_to\_end},i} = T_{NG} + Wait_G + Wait_M + T_{GN} \quad (1)$$

where T_{NG} is the time required for the message to go from the node to the gateway; $Wait_G$ is the time the message spends in the gateway until it is completely uploaded to the mule; $Wait_M$ stands for the time the message is in the mule until it is received by the destination gateway; and T_{GN} is the time required for the message to go from the gateway to the destination node. In Section IV-A we show how these variables are derived for FIFO and Rate Monotonic scheduling protocols, and it is particularly shown in Equations 2 and 3.

A. Node-Gateway

Although the nodes usually have several wireless network capabilities, for simplicity of presentation we analyze only WiFi network interfaces, which is compatible with IEEE 802.11 a/b/g/n/ac. The IEEE 802.11 standard proposes the use of Carrier Sense Multiple Access with Collision Avoidance at the MAC layer. However, its usage cannot guarantee real-time communication, as nodes may find unbounded delay to gain access to the common channel.

For supporting real-time messages, several TDMA variants have been proposed [26]. This schema reserves a slot in every frame for each node that needs to transmit, therefore the clocks of the nodes should be synchronized; typically, by means of GPS UTC. Although the use of GPS represents energy consumption, its usage is necessary for geo-localizing members of the first response teams.

For ease of presentation we can transform the message length C in a function of the period of the frame T_f, and the amount of bytes that can be transmitted in a slot, τ. Therefore, $\epsilon = T_f\lceil \frac{C}{\tau} \rceil$. Thus, the maximum waiting time in the FIFO queue is given by:

$$\sum_{i=0}^{|MQ|} \epsilon_i$$

Each node transmits in a fixed slot time, in every frame T_f. The worst situation for a message in a node is to be generated just after its assigned time slot. In that case, the node will have to wait for the next frame before being able to start the transmission of the message. If the message length C is greater than τ, a total of $T_f = \lceil C/\tau \rceil$ frames would be necessary for the transmission.

Figure 3 shows for a single slot message that, even in the worst case (i.e., when the message arrives just after its slot has passed), it would be delivered within one frame period.

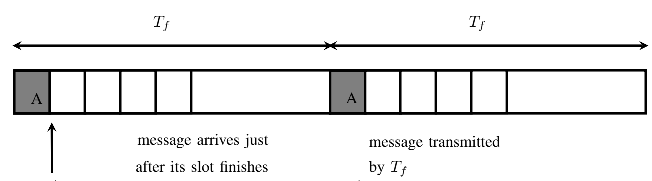

Fig. 3. Message worst-case delay in TDMA

If the node has several messages to transmit, different approaches can be considered. The simplest one is to assume a FIFO order; in that case, the worst case situation occurs when the message is the last one in the node's queue, MQ.

Lemma 1: For a maximum of $|MQ|$ messages in a node, the worst-case delay for a single node to transmit a message to a gateway with FIFO order is given by the following equation:

$$T_{NG} = T_f \sum_{i=1}^{|MQ|} \left\lceil \frac{C_i}{\tau} \right\rceil \quad (2)$$

Please note that the sub-index reflecting the gateway and the node were dropped, because the analysis of the node delay is independent of the other delays.

Proof 1: The node is only able to transmit during one slot in each frame. The order in which the messages are generated in the node is the order in which they are transmitted to the gateway. In each slot, only one message can be transmitted. Therefore, the number of frames needed to finally transmit the message is equal to the time it takes to transmit all messages ahead of it, at the moment the message is generated.

In case that rate monotonic (RM) order is used to transmit the message, each priority level has its queue, where messages wait for being transmitted. In that case, higher priority messages are always dispatched before lower priority ones. Typically, the number of priority levels is restricted for implementation reasons.

Lemma 2: Equation 3 defines the delay to transmit a message from a single node to the gateway with rate monotonic ordering.

$$\min t \ \mathtt{s.t} \ t = T_f \sum_{i=1}^{|MQ|} \left\lceil \frac{C_i}{\tau} \right\rceil + \sum_{j \in HP} \left\lceil \frac{t}{T_j} \right\rceil T_f \left\lceil \frac{C_j}{\tau} \right\rceil \quad (3)$$

where HP denotes the set of higher priority messages.

Proof 2: Equation 3 has two terms. The first one considers the waiting time in a FIFO ordered queue, because the nodes have a limited number of priority levels, so all messages in a particular priority level are scheduled in FIFO order. The second term is the well-known recurrence equation for computing the response time in fixed priorities [27]. The combination of both terms provides the worst-case delay.

Within the first response team, the gateway is another node with its own time slice within the frame. Therefore, the previous analysis is valid for the reverse case, in which messages are transmitted from the gateway to the node. In other words, the GN and NG delays can be analyzed jointly.

B. Gateway-Mule-Gateway

Once messages are queued in the gateway for transmission, the following two hops (gateway-mule and mule-gateway) are analyzed together, given their symmetry. The message exchange between the mule and the gateway begins as soon as they get into communication range, and it continues until they lose contact or the transmission is finished.

When the mule and the gateway are within transmission range, they will exchange messages in a full-duplex way; this period is known as the *transmission window*. The number of messages that they can exchange is then only restricted by the time interval in which they are within range.

At this point it is convenient to note that the proposed model assumes the mule is passing by the gateway in a continuous motion with fixed speed. However, the mule may choose to stop (like a bus at the bus stop) or reduce its speed when it is in contact with a gateway, as a way to enlarge the window to exchange messages. This situation is trivially included in the model by adding to the mule period, the amount of time the mule is stopped in each gateway. Using the same strategy, the reduction of the mules speed can be properly modeled.

The period of the mule, P_{mu}, can then be seen as the sum of two time windows, $P_{mu} = B + W$, where B is the duration of the blind window (i.e., when a gateway cannot transmit to the mule), and W is the duration of the transmission window. P_{mu} represents the interval of time between two consecutive mules connecting to the gateway.

Let us assume that $\forall i \ C_i = C$, the interval of time in which the mule is within transmission range with the gateway is the transmission window, noted as W. Thus, the number of messages ω uploaded to the mule by the gateway in the transmission window can be obtained from equation (4), which is based on a linear path. This simplification can be done since the mule path typically does not differ too much (with respect to time) from a linear trajectory.

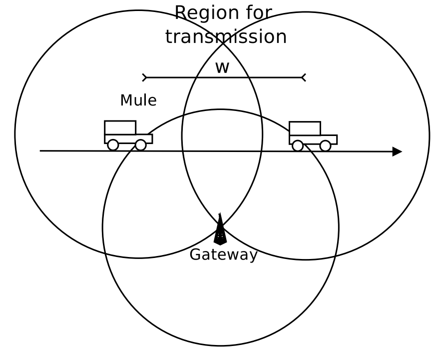

Fig. 4. Gateway/Mule communication range

$$\omega = \frac{W}{C} \quad (4)$$

The mules may have a queue for each gateway, therefore messages sent to nodes belonging to the local network of a particular gateway (i.e., nodes member of the same team than the gateway), are enqueued there. The queuing capacity of a mule is equal to the number of messages that can be delivered during the transmission window. In order to guarantee that all the messages in the system are delivered by their deadlines, we have to ensure that enough mules are present for this, either by enlarging the transmission window or by incorporating more mules to the system. The number of mules in the system is notated ξ.

Mules start their trajectory at a certain gateway. This gateway has a privileged situation with respect to the others, as it will always find an empty slot in the queue, while the following ones will have to wait for the arrival of a mule with empty space in its queue. This fact has to be considered when computing the set of messages that each gateway has to schedule. While the first gateway in the path only deals with the messages originated in its nodes, downstream gateways will have to consider their own messages and also those from the previous ones. Although these messages are not actually served by the gateway, they interfere with the transmission. The position within the path determines the priority in the same way that a "daisy chain" arrangement does it.

The set of messages that gateway G_j has to deal with, is the union of all the messages from its nodes, plus all the messages generated in upstream gateways:

$$M(G_j) = \cup_{j=1}^{i-1} \cup_{i=1}^{n_j} \cup_{h=1}^{\mu_i} m_{jih} \quad (5)$$

where n_j is the number of nodes connected to gateway G_j and μ_i is the number of messages originating in node N_{ji} of gateway G_j. The bandwidth required by the set of messages associated to gateway G_j is given by:

$$U_{M(G_j)} = \sum_{j=1}^{i} \sum_{i=1}^{n_j} \sum_{h=1}^{\mu_i} \frac{C_{jih}}{P_{jih}} \tag{6}$$

Lemma 3: For a gateway G_j to be able to transmit its messages, the bandwidth demand for the set of messages associated to it should be the following:

$$U_{M(G_j)} \leq \xi \frac{W}{P_{mu}} \tag{7}$$

Proof 3: The ratio between the duration of the transmission window W and the period of the mules provides the available bandwidth for each mule. With ξ mules in service, the available bandwidth for transmitting messages is given by $\xi \frac{W}{P_{mu}}$. If the bandwidth required by the messages from a particular gateway is less than the one offered by the mules, all these messages will have the opportunity to be transmitted. Otherwise, if this bandwidth demand is higher, then some messages will be excluded and the system becomes unfeasible.

a) FIFO: The waiting time for a message in a FIFO queue in the gateway is a function of the number of messages Q, generated in the gateway G_j and the interference that upstream gateways G_1 to G_{j-1} may introduce.

Lemma 4: Provided (7) is satisfied, the worst-case waiting time for a message arriving to the gateway G_j is given by:

$$\begin{aligned} Wait_{G_j} &= \texttt{minimum } t \texttt{ s.t. } t \\ &= B + Q \cdot C + \\ &+ \left\lceil \frac{\sum_{j=1}^{i-1} \sum_{i=1}^{n_j} \sum_{h=1}^{\mu_i} \left\lceil \frac{t}{P_{jih}} \right\rceil C_{jih}}{\omega} \right\rceil P_{mu} \end{aligned} \tag{8}$$

Proof 4: The "daisy chain" arrangement of the gateways determines that upstream ones have priority over the downstream ones. For this reason, even if the order is FIFO, a recurrence equation is necessary to compute the waiting time in the gateways. The equation has three terms, where the first one computes the blind window. The second term establishes the time needed to actually transfer all messages from the gateway to the mule, regardless of the messages to be transferred by the upstream gateways. The last term computes the interference of the upstream messages. The ceiling operator accounts for the fact that only an integer number of messages can be generated. As the capacity of the mules is limited to ω messages every P_{mu}, the last term computes the amount of time necessary for a downstream gateway to wait for a mule with enough capacity to accept its messages.

The time spent by messages in the mule is just the time used by the mule to reach the destination gateway, because once messages are uploaded to the mule, they will be delivered at the destination gateway: $Wait_{mu} = T_{trip}$.

b) Rate Monotonic: The use of rate monotonic priority order in the system is conditioned by the "daisy chain" disposition of the gateways. In order to avoid priority inversions that could eventually produce starvation in some gateways, the store-and-forward mechanism is used along the way. Like before, the mules queue length is equal to the amount of messages that can be uploaded to the mule while being in the transmission range of the gateway, ω.

Let us assume $\omega = 2$, therefore we are considering a scenario with three gateways. They are in reverse order of priority and each one has a message to be transmitted to the mule. Therefore, the first message has the lowest priority, but as it is the first in the "daisy chain", it is uploaded to the mule. In the second gateway, the medium priority message is uploaded. When the mule gets to the third gateway, the high priority message has to be uploaded to prevent a priority inversion, and the lowest priority message is exchanged by the highest priority one. To do this, the transmissions between the gateways and the mules are assumed to be full-duplex.

Like in the FIFO case, gateways downstream have to consider the interference of higher priority messages from upstream gateways. Note that the transmission order is not affected by the gateway position; it is only affected by the priority of messages, making the overall system fair. Like in the previous case, every message remains in the mule for the time needed to arrive to destination, and this is independent of the message priority.

Lemma 5: Under Rate Monotonic order and subject to equation (7), a message m of priority π will have a worst-case delay (in the gateway-mule-gateway path) given by the following equation:

$$\begin{aligned} Wait_{G_j} &= \texttt{minimum } t \quad \texttt{s.t. } \quad t \\ &= \sum_{\forall m \in \pi} C + B \left\lceil \frac{t}{P_{mu}} \right\rceil + \sum_{\forall \chi \in HP} \left\lceil \frac{t}{P_{\chi}} \right\rceil C \end{aligned} \tag{9}$$

Proof 5: The rate monotonic recurrence equation should be solved for all gateways simultaneously. This is because messages in the mule with a priority lower than messages waiting in a gateway, are exchanged in a store-and-forward process. Therefore, a message will have several stop-overs before actually getting the destination node. In order to consider this, messages have a double indexing order. The first one is given by the priority and the second considers the gateway position. Due that, given two messages with the same priority, the one coming from the more upstream gateway is delivered first. In this case, the recurrence equation is similar to the one proven in [27].

c) Mule transportation time: In both cases, FIFO and RM, T_{trip} is the time spent by the message in the mule, which corresponds to the time spent by the mule to go from the gateway where it got the message to the destination node, through its fixed path. Clearly, this is independent of the scheduling algorithm that is chosen and depends only on the technology used for the mules and other optimization criteria (e.g., saving fuel).

C. Scheduling Condition

Lemma 6: An opportunistic network operating with mules and gateways implementing FIFO or RM order is schedulable if:

$$\forall m_{jih} \quad D_{jih} \geq T_{\texttt{end\_to\_end},jih} \tag{10}$$

Proof 6: Every message should arrive, in the worst-case, before its deadline for the system to be real-time schedulable. Given that we can compute the end-to-end delays for each message, if they meet their deadlines, the system is schedulable.

D. Analysis with Other Parameters

In the new scheme described above the mules represent critical components as their frequency, speed and transmission window define the actual throughput of the OppNet. In this section, we propose to vary the mule parameters to illustrate how they can experimentally affect the schedulability conditions of the network. We have made the assumption that only one mule should exchange messages with a given gateway at a time. With this constraint, there are two possible improvements: increasing the number of mules or their speed.

The number of mules can be increased up to the point where there is no more blind windows in the gateways, as mules are coming back-to-back one after the other, separated by W/S, where S is the mules speed. This will provide a continuous transmission window raising the available bandwidth to 100%, assuming that gateways can only transmit on one channel/frequency.

The speed of the mules was considered constant. However, it can be varied in such a way that the transmission windows are enlarged while the mule needs to exchange messages with the gateways. In that case, mules can move quickly between successive gateways to keep the period constant. The mule should also consider changing its speed taking into account the distance between two successive mules. By doing this, the available bandwidth can also be improved, but it cannot reach 100% if there is only one mule. This is true assuming the distance between the gateways is positive and the maximum speed of the mule is bounded, as the mule will take time to actually move from one gateway to the next one.

The equations of the model are valid even if the mule does not follow a circular path. Although in that case some gateways will be visited by the mule more often than others, the whole transmission window for a node and a particular mule can be kept stable varying the mule speed as indicated before. Performing these adjustments is highly feasible in most real-time work scenarios that require the use of mules, because the transmission windows usually represents a very small portion of the blind window of the mule (i.e., the time period used to go from one gateway to the next one). Regardless the feasibility of considering several types of paths for the mules, the use of suitable message scheduling strategies and queue lengths for these mobile nodes remain being important design aspects, since it allows maximizing the throughput of these networks and the delivery of messages before the deadline. In this sense, the network designers play an important role establishing the appropriate values for these network parameters.

Next two sections present the performance evaluation of the proposed model using an analytic approach based on the equations introduced in this section. First, we use a synthetic example to show the main properties of the model. Then, we use the scenario of a real fire incident [28], [29], as case study to show the potential advantages of using the proposed message propagation model to support firefighters communication during the response activities.

V. Model Evaluation Using a Synthetic Case

In order to show the performance of the proposed model, we present a synthetic scenario that simulates the interactions among the participants in a disaster relief effort. Figure 5 presents the physical layout considered in this example. Although this layout is only a portion of the response activities typically conducted in the field, it is large and diverse enough as to illustrate the capabilities and properties of the proposed model.

Such example scenario considers three gateways (G_1, G_2, G_3) that are capable of sending messages, and there are also three mules (M_1, M_2, M_3) with a period $P_{mu} = 5$. All the gateways have the same transmission and blind windows, $W = 2$ and $B = 3$ respectively. Typically, the Incident Commander (IC) is the main destination of the messages delivered by the gateways, since he has to coordinate the activities of all teams working in the field. The IC is located at the command post, just before the first gateway, and the mules begin their trip from such a point as shown in Figure 5. Consequently, the round trip for a mule is equal to 15 slots, and the maximum trip times from gateways G_1, G_2, G_3 to the IC are 13, 8 and 3 time units (or slots) respectively.

In the next subsections we analyze the model performance in the two stages described in the previous section; i.e., node-gateway and gateway-mule-gateway scheduling. In this last case, only a few messages from the nodes are effectively transmitted to the mule, since not all the messages from nodes are finally sent through the network.

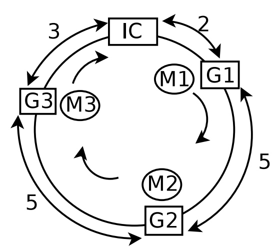

Fig. 5. Example layout configuration: incident commander, three gateways, and three mules that travel clockwise

A. Node-Gateway

In this example we consider message exchange between G_1 and its three nodes, each of which has 2 messages to transmit per period. The frame has six slots, $T_f = 6$ in which only three are allocated to the nodes in consecutive way. Each node has maximum queue size $|MQ| = 2$.

Let us assume $\mathbf{N}_{G_1} = \{N_{11}, N_{21}, N_{31}\}$. The sets of messages are as follows: $M(N_{11}) = \{m_{111}, m_{112}\}$, $M(N_{12}) = \{m_{121}, m_{122}\}$, $M(N_{13}) = \{m_{131}, m_{132}\}$, $m_{111} = (10, 1, 30, 1)$, $m_{112} = (30, 1, 40, 2)$, $m_{121} =$

$(10, 1, 30, 2)$, $m_{122} = (30, 1, 40, 2)$, $m_{131} = (10, 1, 30, 1)$ and $m_{132} = (30, 1, 40, 2)$. As it was defined in section III, the first element in the tuple is the period, the second the message length in slots, the third is the relative deadline, and the last one the message priority.

Figure 6 shows the message transmission times between the nodes and the first gateway for FIFO and RM scheduling policies. The arrows labels indicate the instants at which the messages are generated. Using equation (2), each node has two messages to transmit with a FIFO ordering. By instantiating this equation we can obtain the waiting time in the node:

$$T_{NG} = 6 \sum_{i=1}^{|2|} \left\lceil \frac{1}{\tau} \right\rceil = 12$$

In the case of Rate Monotonic, the messages with shortest periods are transmitted first. In this case, we have to instantiate the recurrence equation (3).

$$\min t \ \texttt{s.t} \ t = T_f \sum_{i=1}^{|MQ|} \left\lceil \frac{C_i}{\tau} \right\rceil + \sum_{j \in HP} \left\lceil \frac{t}{T_j} \right\rceil 6 \left\lceil \frac{C_j}{\tau} \right\rceil$$

The solutions for this example are: 6 for $m_{111}, m_{121}, m_{131}$ and 12 for $m_{112}, m_{122}, m_{132}$. These are the worst-case response times, as we can see in Figure 6, messages with period 10 are sent in slots 4, 5 and 6, while messages with period 30 are sent in slots 10, 11 and 12.

B. Gateway-mule-gateway

For calculating the transmission delay involving the gateway, the mule and the gateway, we assume that the gateways have the following sets of messages to transmit. For the case of G_1, only two out of six messages are forwarded. Once again, the first element in the tuple is the period, the second the message length, the third is the relative deadline, and the last one the message priority. For ease of notation we drop the third sub-index.

$$G_1 = \{m_{11}, m_{12}\} = \{(10, 1, 30, 1); (30, 1, 40, 2)\} \quad (11)$$
$$G_2 = \{m_{21}, m_{22}\} = \{(15, 1, 30, 2); (30, 1, 40, 3)\} \quad (12)$$
$$G_3 = \{m_{31}, m_{32}\} = \{(10, 1, 30, 1); (30, 1, 40, 3)\} \quad (13)$$

With this configuration, the load for gateways G_2 and G_3 computed with equation (5) is the following:

$$M(G_2) = \{m_{11}, m_{12}, m_{21}, m_{22}\} \quad (14)$$
$$M(G_3) = \{m_{11}, m_{12}, m_{21}, m_{22}, m_{31}, m_{32}\} \quad (15)$$

Figure 7 shows the messages delivery in the system with a FIFO priority assignment; where HP stands for high priority (equal to 1), MP is medium priority (equal to 2), and LP is low priority (equal to 3). We consider the worst case situation in which the messages have to wait for a mule with empty slots. Each row in the Figure represents a gateway. Using equation (8) the worst-case waiting time in the gateway can be computed for each message. For G_1, as it is the first gateway in the line, the delay is just 5 slots. For the second gateway, G_2, the delay is 10, and for the last one, G_3 is 20. When the trip time of the mule is added, we can calculate the worst-case transmission times, which are 18, 18 and 23 for gateways G_1, G_2 and G_3, respectively.

Figure 8 shows the temporal evolution of the messages in the mules when RM priority assignment is used. The three gateways depicted can handle three priority levels for messages.

We can see that the lower priority message of G_1 is stored in G_2, and it is replaced by its medium priority message. In G_3 this medium priority message is stored and replaced by the higher priority message. As we can see, the higher priority message in G_3 is delivered before, avoiding thus priority inversions. Using equation (9) to compute the worst-case transmission time, we can see that the messages in the first gateway need 17 and 23 slots respectively to reach the IC. In the second gateway the messages require 17 and 28 slots, and finally in the third gateway they require 8 and 32 slots. This shows that the RM approach helps improve the delivery time of higher priority messages. For instance, in the FIFO scheduling the highest priority in the last gateway has to wait for up to 18 slots to arrive to the destination, while in RM it waits at most for 8 slots.

VI. Model Evaluation Using a Real-World Emergency Scenario

The description of this incident comes from the official incident report of the Yarnell Hill Fire [28] that affected the Yarnell village area (Arizona, USA) from June 28^{th} until July 3^{rd}, 2013. The limitations for conducting the first response activities, in terms of communication, coordination and graphical information support, took the life of 19 firefighters in such an incident. Next we briefly describe the first response process based on the official reports, and analyze the communication limitations that led to catastrophic results. Then, we hypothesize about how the support provided by the proposed model could have improved the communication capability in the field, and thus reduce the impact of such an incident. The analysis of the communication support provided by the proposed model is done instantiating the equations introduced in section III.

A. Yarnell Hill Fire Case Study Description

In the late afternoon of June 28^{th}, 2013, a fire started in a boulder field in steep terrain close to Yarnell village. The place had no access to vehicles and the fire was about one-half acre in size. The firefighters saw minimal fire activity or spread potential; therefore, they decided to take action during the next day, since they had several safety concerns with putting firefighters on the hill overnight. In consideration of these and other factors, the Incident Commander prepared for full suppression on the following morning. Figure 9 presents the way in which the fire expanded from June 29^{th} until July 3^{rd}.

During the next day, resources held the fire in check until mid-afternoon when winds increased and the fire was spotted outside containment lines. In the evening, the incident was

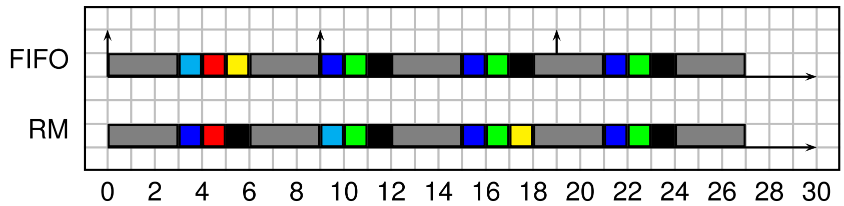

Fig. 6. TDMA message scheduling in the first gateway: m_{111} blue, m_{121} green, m_{131} black, m_{112} cyan, m_{122} red and m_{132} yellow. First row shows the FIFO scheduling in the nodes, and the second row indicates the RM scheduling.

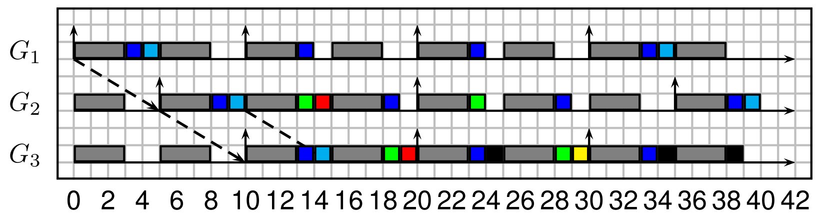

Fig. 7. FIFO order: m_{11} blue (Priority 1), m_{12} cyan (Priority 2), m_{21} green (Priority 2), m_{22} red (Priority 3), m_{31} black (Priority 1) and m_{32} yellow (Priority 3).

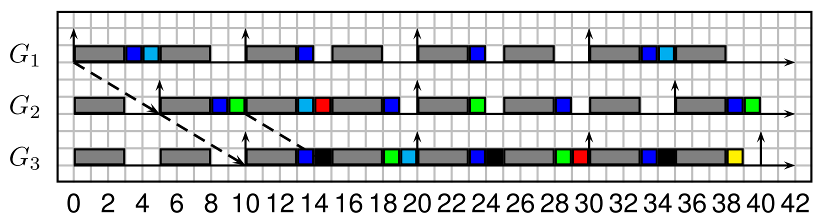

Fig. 8. RM order: m_{11} blue (Priority 1), m_{12} cyan (Priority 2), m_{21} green (Priority 2), m_{22} red (Priority 3), m_{31} black (Priority 1) and m_{32} yellow (Priority 3).

reclassified and additional resources were provided for the next morning.

The fire grew to an estimated 300 to 500 acres by the morning of June 30^{th}. With the spread of the fire, the incident was re-categorized, and an incident management team was designated and new firefighting crews were allocated in the area around the fire perimeter. Until mid-afternoon the fire propagated to the northeast, threatening the Peeples Valley village and Model Creek structures. In fact, Peeples Valley was evacuated. However, at 3:50 pm, the wind shifted and the fire started pushing aggressively to the southwest toward Yarnell village. In the southwest perimeter of the fire, only the specialized Granite Mountain Interagency Hotshot Crew (IHC) firefighter company was working.

At this time, there was no communication capability between the incident commander and the IHC team, given the distance between these nodes and the mountainous geography of the area. The Incident Commander assumed that the IHC team was in the “black”, that is, where the fire has already burnt the field and generates an inhospitable but safe place. The air support in charge of dropping retardant to the fire received contradictory information and they also assumed the Granite Mountain IHC team (Division A) was safe in the black, which was not correct. Due to the lack of communication, Division A left the southwest side and tried to reach a safety place at the worst moment, and at about 4:42 pm the Granite Mountain IHC team was trapped in a canyon by the fire.

Figure 10 shows the map of the affected area at the end of the incident, and the approximate positions of the firefighter teams (Divisions A, C, F, T and Z) and the incident commander (Command Post). There were also two teams of specialists in evaluation of civil infrastructure (structure teams) supporting the process; one of them was in Peeples Valley and the other in Yarnell village.

B. Potential Scenario Using the Proposed Model

Figure 11 represents a possible deployment of an opportunistic network, based on the proposed model, which uses mules to support the message transmission between the IC and the Firefighting Divisions during the morning of June 30th. Figure 12 represents the situation during such afternoon, once the wind shift produced the change in the fire direction and speed. In the first case, the Divisions are quite close to each other and moving back trying to protect the infrastructure. They were using the VHF radio to communicate with each other, coding the information in different channels for each team, namely the command post and the air support. This mechanism was classified as insufficient in the official report of the incident [28].

In order to illustrate the potential contribution of the proposed communication model, let us consider the situation during that morning (June 30^{th}). As it can be seen from Figure 10, the distance between the different Divisions and the IC

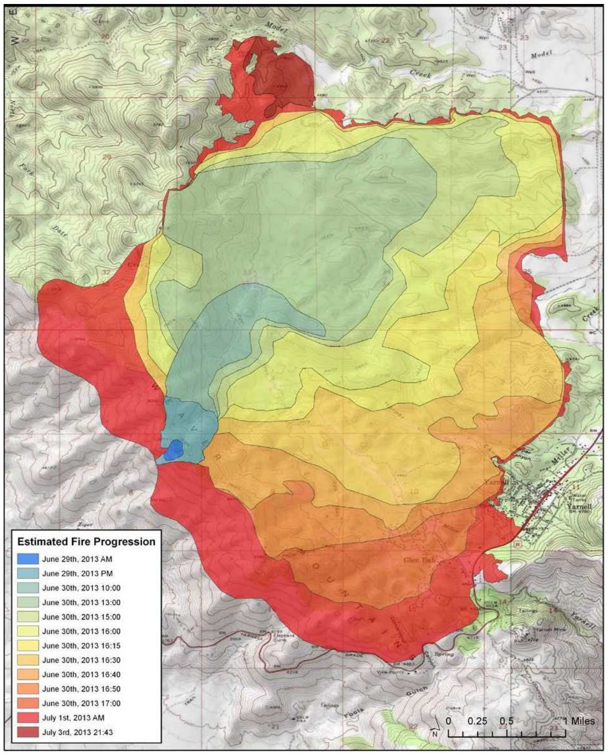

Fig. 9. Yarnell Hill fire evolution (based on [29])

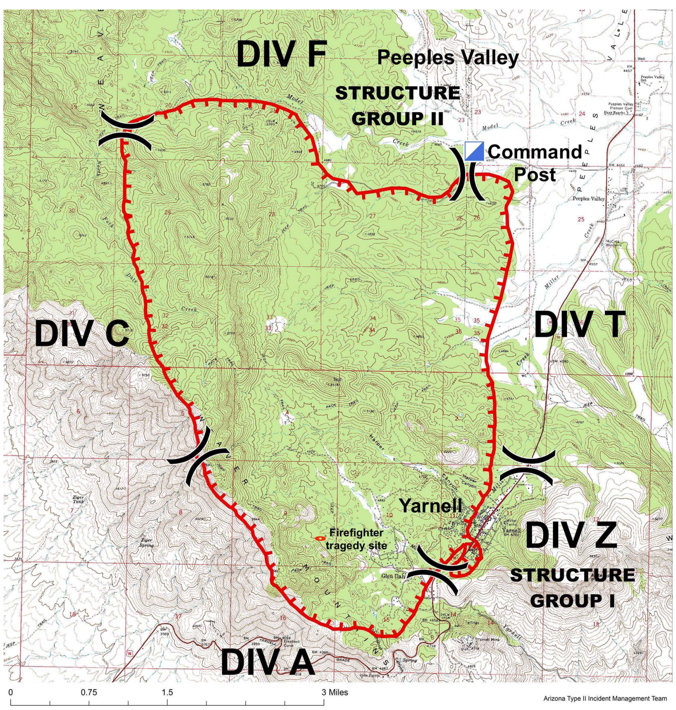

Fig. 10. Yarnell Hill fire situation on June 30^{th} (based on [29])

is not too long. However, only the IC was connected with Yarnell village through route 89. The rest of the area is difficult to access with steep slopes, boulders and ridges. Division A was near Yarnell at the heel of the fire on a two track road (ungraded dirt road where people have driven enough times to leave two tire ruts in the soil). In this case, mules may have been implemented with enduro motorcycles or drones.

Given the features of the terrain, the smoke in the area and the risk proper of these incidents, we can expect that mules move not very quickly. Let us suppose they can do it at an average speed of 15 km/h. As firefighters are in every side of the fire, three different branches are possible (Fig. 11). In this case, one mule may connect Divisions F and C with the Incident Commander. This latter unit and Divisions T and A may communicate through a second mule, while the communication with Divisions Z can be done using a third mule. This last mule may be implemented using a 4x4 vehicle moving on route 89. Eventually, this mule may provide connectivity with Division A and T through the south, if the fire cut the line between the Incident Commander and Division T.

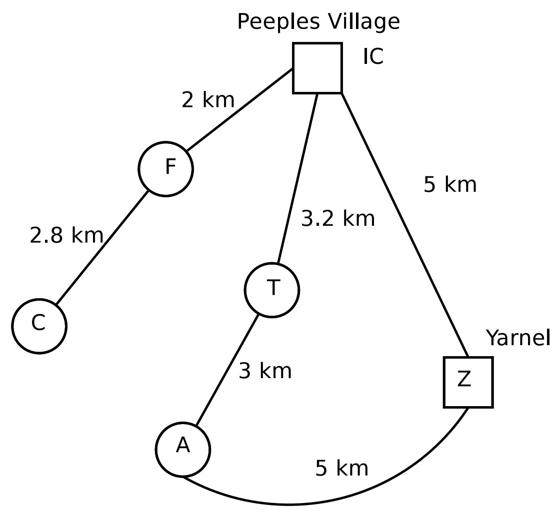

Fig. 11. Opportunistic network model that could be used to provide digital real-time communication during the morning of the June 30th

In the first branch, the mule moves back and forth through a preestablished linear path covering 4.8 km each way. The messages exchanges are from/to the IC, and the linear path of the mule does not affect these exchanges since the queue of the mule is large enough to simultaneously store all the priority messages. Moreover, the message deadlines are aligned with the time required by the mule to cover the route. A round trip of this mule consumes 40 minutes; therefore, in the seven hours of interest a mule covers this route more than 10 times. We consider that the distance between the divisions is shortened as the fire keeps advancing.

In the second branch, the initial round trip requires 50 minutes; therefore, a mule may cover the route 8 times in the seven hours of interest. Finally, the third branch requires 40 minutes. In this case, Division A will have two paths to send and receive information to and from the Incident Commander through a digital link. This link allows the exchange of graphical information (e.g. maps and pictures), contributing thus to keep the resilience of the teams against unexpected changes in the first response scenario.

Beginning at 10:00 am, Division A would have received updates two times per hour, and provided information again twice per hour. These information exchanges are complementary to those performed through radio systems and face-to-face interactions.

During the afternoon the wind shifted, and therefore fire changed in direction modifying the previous locations of the teams (i.e., changing the network topology). In our simulated scenario, the middle branch would be no longer present, as Division T should back off to protect themselves and the civil infrastructure in Peeples Valley and Yarnell village (Fig. 12). The branch at the east side of the fire, that involves Divisions C and F, is communicated through route 89. That branch is also connected to the IC, the Divisions T, Z and A, and the structure team located at Yarnell. The information in this response scenario can be updated in at most half an hour (or probably less time), therefore the information on the wind shift would have arrived early to the teams preventing thus the tragedy.

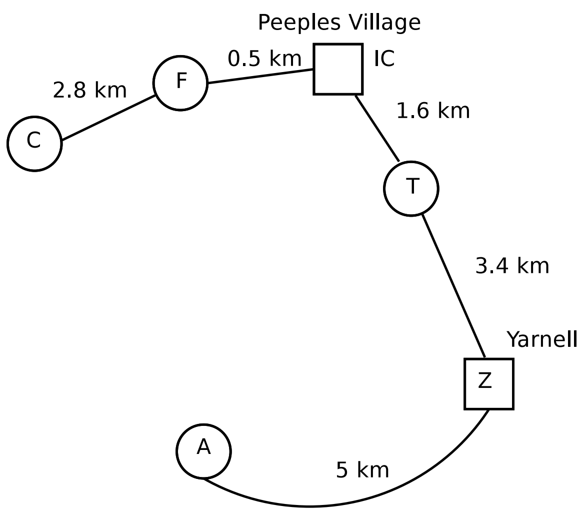

Fig. 12. Opportunistic network model for the afternoon of June 30th

In this example, the choice of a FIFO or RM message scheduling policy may be really important, as high priority messages should arrive as soon as possible to both, the IC and the response teams. In this sense, the FIFO order cannot guarantee the on-time delivery of the priority messages, therefore it is more convenient to use a RM scheduling strategy.

VII. Verification of the Analytic Results

In order to show the overall performance of the proposal, this section presents the simulations of the communication scenarios described in Section V (synthetic case) and also in Section VI (the Yarnell Hill fire incident). The simulation results illustrate the message delay and the network performance in both scenarios, and allow to confirm the results obtained through the analytic evaluation presented in the previous sections. In what follows we explain with more details the experimental framework, and then the tests performed to validate the capabilities of proposed message dissemination model.

A. Experimental Framework

The simulations were implemented using SimPy [30], that is a process-based discrete-event simulation framework implemented in Python programming language. The simulations implemented a model of the nodes, mules, teams and links among them. The node-gateway links were implemented considering a TDMA schema as described on Section IV-A. The gateway-mule links were implemented using the space-time graph that represents the connectivity model described on Section III.

Other modeling considerations made in these simulations are the following: (1) all messages long only 1 time slot, (2) we use the time slot as the time unit for the evaluation, and (3) message generators start at different times since they use a random initial delay.

Once the system is configured in the simulator, the experiments were run with diverse release times for the messages in the source nodes. With these variations we can evaluate the network behavior and also the loads in the intermediary nodes for each path. Specifically, we calculate the following metrics:

1) End-to-End delay, in terms of time slots.
2) Packet Delivery Ratio, i.e., the ratio of successfully received messages compared to the total number of sent messages.
3) Network Goodput Ratio, i.e., the ratio of messages received before their deadline, compared to the total number of sent messages.

B. Validation of the Synthetic Case

The first validation involved the scenario of the synthetic example presented in Section V. As shown in Figure 5, this scenario considers three rescue teams with their gateways (G1, G2 and G3), the incident commander (IC) and three mules (M1, M2 and M3). Taking into account these components, we simulated the end-to-end communication, and not just the fragment of interactions that the example wants to illustrate. Next we present the simulation results for both, the node-gateway and gateway-mule-gateway scenarios in order to confirm the results shown in Section V.

1) Simulations node-gateway: Figure 13 shows the empirical cumulative distribution-function (ECDF) of end-to-end message delays for the FIFO and RM scheduling strategies, considering the node-gateway interactions. In this figure there are messages without delay, because they did not reach the destination. Messages that do not meet with their deadline are discarded by the gateways or mules. In this case, the majority of discarded messages have the most restrictive deadline (30 time slots). The Packet Delivery Ratio (PDR) in this scenario is 65.1% and 88.2% for FIFO and RM scheduling strategies respectively. The Goodput Ratio is the same as the PDR, i.e., 65.1% and 88.2% for FIFO and RM respectively. All these messages were received before their deadline. These results indicate that the RM scheduling strategy allows to achieve a better PDR and a lower transmission delay than the FIFO strategy; therefore, this strategy is more suitable for supporting real-time message dissemination.

Figure 14 shows the boxplot statistical representation of end-to-end delays, grouped by message type, for the FIFO

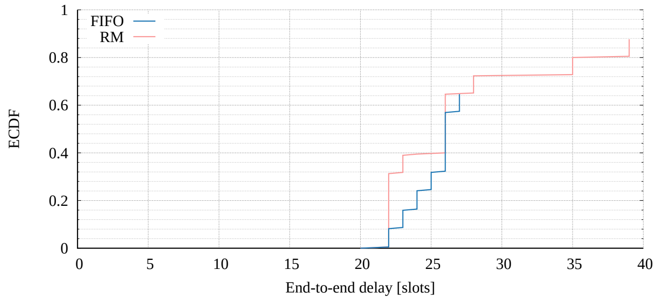

Fig. 13. End-to-end message delays for the interaction node-gateway

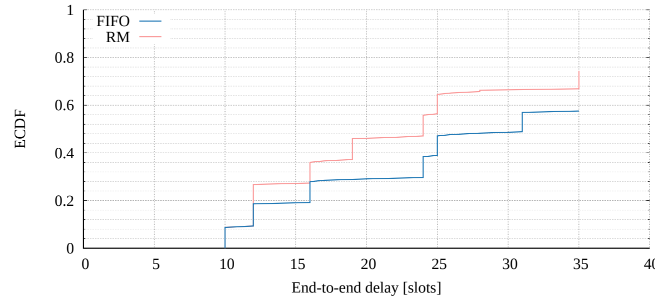

Fig. 15. End-to-end message delays for the scenario gateway-mule-gateway

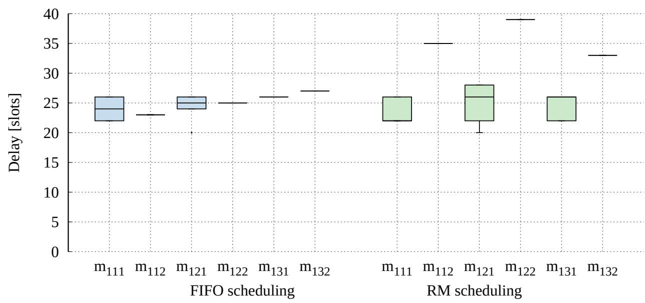

Fig. 14. Message delays by message type for the interaction gateway-mule-gateway

and RM scheduling strategies. This figure shows a better PDR for the messages m_{111}, m_{121} and m_{131} using RM than using FIFO. The other messages achieve a similar PDR in both strategies. The messages m_{111}, m_{121} and m_{131} are the most intensive in terms of time slots used per period, and they have the most restrictive deadline (30 time slots). Moreover, the messages m_{111} and m_{131} are the most priority ones. The cost of the improvement reached by the RM scheduling strategy involves to have a worse delay for messages m_{112}, m_{122} and m_{132}. The messages m_{112}, m_{122} and m_{132} have a more relaxed deadline (40 time slots), with some margin to be delayed for meeting the deadline.

2) Simulations gateway-mule-gateway: Similar to the previous case, Figure 15 shows empirical cumulative distribution-function of end-to-end message delays for the FIFO and RM strategies, but considering the scenario gateway-mule-gateway. The Packet Delivery Ratio and also the Goodput Ratio are both 58.1% and 75% for FIFO and RM keeping thus the previous tendency. Once again, these results indicate that using a RM strategy allows to obtain a better PDR and a lower transmission delay than when using a FIFO strategy. This suggests a usage preference of RM over FIFO to support real-time communication.

In this case, the messages m_{22} and m_{31} achieve a better PDR when using a RM strategy, and this ratio for the other messages remains similar regardless the scheduling strategy being used. It is important to notice that the transmission window of IC is too short as to deliver all the messages carried by the mules. Therefore, ordering the messages by priority (as RM does) is a good strategy to deal with this issue. Summarizing, the simulation results shown in this section are aligned with those coming from the analytical evaluation, confirming thus the properties of the proposed model for supporting real-time communication on OppNets.

C. Yarnell Hill Fire Use Case

This communication scenario is based on Figure 11, where five rescue teams (Divisions A, C, F, T and Z), the incident commander (IC) and three mules (M1, M2 and M3) are involved in the emergency response process. This figure also shows the space-time graph according to the connectivity model defined for such a scenario.

1) Modeling considerations: In this simulation the transmission slot has 1 second of duration, since it keeps a good balance between message transmission capability and time required by the mules to complete a trip. In this case the mules travel back and forth through the same route as shown in Fig.12. The average cross-country speed of the mules was set in 15 km/h, and 45 km/h when they move on the road. The mules speeds and the distance among the divisions were modelled using random variables with an uniform distribution; therefore, different trips of a mule could involve a different number of time slots. The transmission windows between a mule and a gateway is 200 meters (it is in open areas), which corresponds to 48 slots when the mule is moving cross-country, and 16 slots when it is on the road. The mules can regulate their speed to enlarge the transmission windows, and thus ensure that all critical messages are exchanged between the mule and the gateway. The largest transmission window is usually the one involving the command post, since most messages are exchanged with the incident commander.

The simulation considers two types of messages (type 1 and 2), where the message type represents its priority for delivery. The priority of type 1 messages is higher than type 2. All messages are generated in the teams or in the command post. In the first case, the message destination is always the IC, and in the second case the destination is one or more teams. In this simulation the messages type 1 are defined as $m_1 = (600, 1, 3600, 1)$ and messages type 2 are specified as $m_2 = (1000, 1, 3600, 2)$ where the first parameter represents the period or minimum intergeneration time of the message in terms of slots, the second parameter is the worst-case time for transmitting a message (also in terms of slots), the third one is the deadline, and the last one is the message priority (or message type).

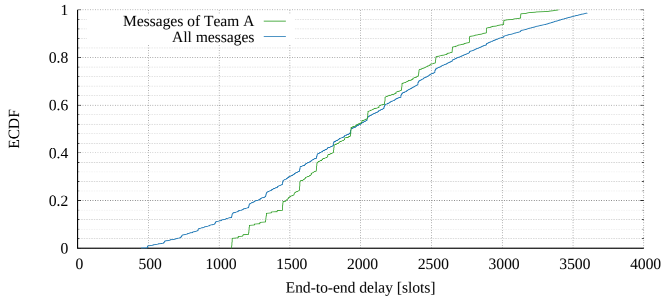

Fig. 16. End-to-end message delays

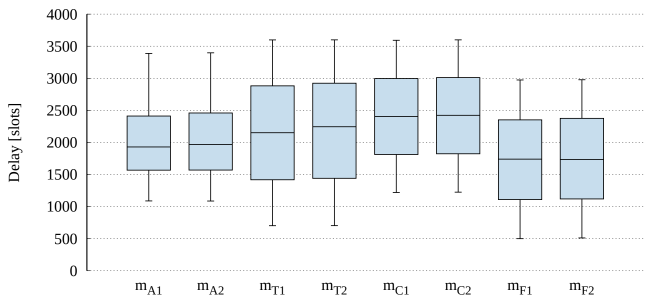

Fig. 17. Message delays by message type

2) Simulation results: Figure 16 shows the empirical cumulative distribution-function of end-to-end message delays using RM scheduling strategies. The results of using RM and FIFO are quite similar; therefore, we will show only the first scheduling strategy. The differences between both strategies become more evident when there is high message congestion in a gateway (e.g., in the gateway of the IC). In that case, the message priority considered in RM makes a difference.

As in the previous case, the PDR and the Goodput Ratio have the same value; in this case it is 98.1%. Particularly, in the case of the messages from/to Division A, the PDR and the Goodput Ratio are 100%, which means that such a Division would be able to exchange all critical messages, avoiding thus its isolation.

Figure 17 shows the boxplot statistical representation of end-to-end delays, grouped by message type. Only messages from the response teams to IC are represented, since the flow in the opposite direction has a similar representation. The results show a similar behavior for delivering every message type, and there is a large dispersion among messages belonging to the same type. There are two main reasons for this situation: (1) there are variations in the duration of the mules trip, and (2) there is a coincidence factor between the arrival of the mule at the gateway and the messages to be transported by the mule. The higher the coincidence of the arrival time to the gateway, the lower the waiting time of the messages.

Figure 18 shows empirical cumulative distribution-function of message delays of Division A. Once again the results shows a positive impact due to the use of a RM over a FIFO scheduling strategy. Particularly, there is a lower delay of priority messages $m_(A1)$ versus the rest of the messages $m_(A2)$.

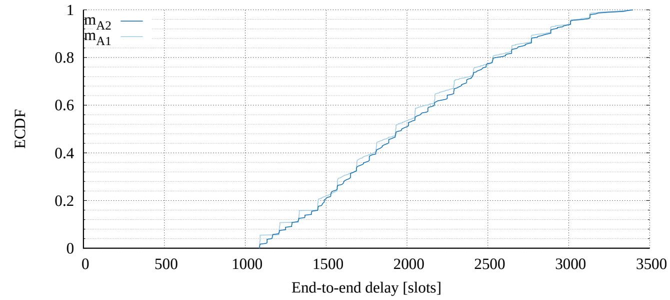

Fig. 18. Message delays of Division A

On the one hand, these results confirm the properties of the proposed model to support real-time communication on OppNets. It also shows that this communication strategy could have contributed to change the history of the Yarnell Hill incident.

On the other hand, these results shows the suitability of the analytical representation of the proposed model. This allows researchers and practitioners to model and evaluate the properties of these networks spending an effort considerably lower than using simulations. Thus, prototyping real-time OppNets and evolving their design based on their evaluation results become a much more feasible activity, which can be conducted in short-time periods and with limited resources.

VIII. Conclusions and Future Work

Opportunistic networks are one of the main IoT enablers to support communication in several application domains. These networks operate with a best-effort paradigm, and their dissemination strategy is subject to the participation of nodes for storing, transporting and eventually delivering the messages to the destination. In many of application domains, like in disaster relief efforts, the solutions need to count on real-time communication. Regardless the ample research done on OppNets, and to the best of the authors knowledge, there is no proposal that present a real-time analysis of the message delivery in these networks. Therefore, the communication limitations affecting these work scenarios cannot be certainty addressed using the current OppNets proposals.

Trying to deal with such a challenge, this paper presents a network model to provide real-time communication in OppNets. The model introduces a bounded message propagation schema that involves IoT-enabled devices as nodes. The suitability of the model was analyzed using two scheduling policies: FIFO and RM. While the first one facilitates the unrestricted information flow, the second one introduces priorities that guarantee the delivery of important messages. In application domains, like in disaster relief scenarios, ensuring the delivery of high priority messages (e.g., alarms or orders from the IC) makes an important difference; therefore, the model proposes to use RM message scheduling strategies.

The network model provides predictability to real-time message propagation in an OppNet, which is the main contribution of the paper. This message propagation considers the eventual participation of mules (when required) as special nodes moving around the stationary components and exchanging the necessary information with them. The model was specified through a set of equations that capture the network behavior and allows to create particular instances of a network and determine its properties spending a low effort.

The proposed model was evaluated using both, an analytical approach and simulations. Every evaluation strategy considered the use of the model in two study scenarios; the first one was a synthetic case study, and the second one was a disaster relief effort based on a real-world incident. The results obtained through both approaches (i.e., using the analytical evaluation and the simulations) were consistent and highly positive, showing the capability of this proposal to support real-time communication on OppNets.

Although the proposed communication model is presented and evaluated considering a disaster relief scenario, it should be also suitable to provide communication support in other application domains with similar restrictions; for instance, to conduct remote and distributed monitoring of critical civil infrastructure and natural resources (e.g., volcanoes and rivers), to support the early detection of natural hazards (e.g., floods, tsunamis, and wild fires), and to assist the self-evacuation of the people under risk conditions (e.g., after an earthquake, a volcano eruption or a tsunami warning). In this sense, the proposed model opens several opportunities to advance the knowledge in this area, and improve the development of interaction technology that requires opportunistic real-time communication support. The ubiquitous computing research community and also the software and communication industry can take advantage of it in order to create new solutions or improve those already implemented in domain.

Next steps in this initiative considers performing a real-world proof-of-concept to verify the results obtained from the analytical evaluation and the simulations. This would allow determining more accurately the impact of this proposal for both, the research community and the industry.

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